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GRB010921: LOCALIZATION AND OBSERVATIONS BY THE HETE SATELLITE

G. Ricker[1] K. Hurley[6] D. Lamb[9] S. Woosley[8] J-L Atteia[4] N. Kawai[2,16] R. Vanderspek[1] G. Crew[1] J. Doty[1] J. Villasenor[1] G. Prigozhin[1] G. Monnelly[1] N. Butler[1] M. Matsuoka[13,15] Y. Shirasaki[14,15,16] T. Tamagawa[16] K. Torii[16] T. Sakamoto[2,16] A. Yoshida[13,16] E. Fenimore[3] M. Galassi[3] T. Tavenner[3] T. Donaghy[9] C. Graziani[9] M. Boer[4] J-P Dezalay[4] M. Niel[4] J-F Olive[4] G.Vedrenne[4] T. Cline[9] J.G. Jernigan[6] A. Levine[1] F. Martel[1] E. Morgan[1] J. Braga[10] R. Manchanda[11] G. Pizzichini[5] K. Takagishi[12] M. Yamauchi[12]
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ABSTRACT

On September 21 at 18950.56 SOD (05:15:50.56) UT the FREGATE γ-ray instrument on the High Energy Transient Explorer (HETE) detected a bright gamma-ray burst (GRB). The burst was also seen by the X-detector on the WXM X-ray instrument and was therefore well-localized in the X direction; however, the burst was outside the fully-coded field-of-view of the WXM Y-detector, and therefore information on the Y direction of the burst was limited. Cross-correlation of the HETE and *Ulysses* time histories yielded an Interplanetary Network (IPN) annulus that crosses the HETE error strip at a $\sim$45 degree angle. The intersection of the HETE error strip and the IPN annulus produces a diamond-shaped error region for the location of the burst having an area of 310 square arcminutes. Based on the FREGATE and WXM light curves, the duration of the burst is characterized by a t_{90} = 18.4 s in the WXM 4 - 25 keV energy range, and 23.8 s and 21.8 s in the FREGATE 6 - 40 and 32 - 400 keV energy ranges, respectively. The fluence of the burst in these same energy ranges is 4.8 10^{-6}, 5.5 10^{-6}, and 11.4 10^{-6} erg cm^{-2}, respectively. Subsequent optical and radio observations by ground-based observers have identified the afterglow of GRB010921 and determined an apparent redshift of z = 0.450.

Subject headings: gamma rays: bursts (GRB010921)

1. INTRODUCTION

As has long been recognized, accurate locations and rapid follow-up observations in many wavelengths are central to understanding the nature of gamma-ray bursts. For this reason, a strategy evolved in the late 1970's and early 1980's (e.g., Woosley et al. 1982) to detect GRBs, not only in gamma-rays, but also in emitted X-rays and optical light. While detection of short transients at the lower energies posed observational challenges, and the strength of the optical signal was unknown, the possibility of arc minute localizations deduced from the X-rays that were known to be present was very appealing. This strategy was implemented in the HETE-1 (High Energy Transient Explorer) satellite, which was unfortunately lost due to a rocket failure on 1996 November 4, and in the highly successful *BeppoSAX* Mission (Costa et al. 1997).

The HETE-2 satellite (henceforth simply "HETE"), which was successfully launched into equatorial orbit on 9 October 2000, is the first space mission entirely devoted to the study of gamma-ray bursts (GRBs). HETE utilizes a matched suite of low energy X-ray, medium energy X-ray, and gamma-ray detectors mounted on a compact spacecraft. A unique feature of HETE is its capability for localizing GRBs with $\sim$1-10$'$ accuracy in real time aboard the spacecraft. GRB locations are transmitted, within seconds to minutes, directly to a dedicated network of telemetry receivers at 13 automated "Burst Alert Stations" (BAS) sited along the satellite ground track (Villasenor et al 2002). The BAS network then re-distributes the GRB locations world-wide to all interested observers via Internet and the GRB Coordinates Network (GCN) in $\approx$1 s (Vanderspek et al. 2002, Barthelmy et al. 2002).

[1] Massachusetts Institute of Technology, Center for Space Research, Cambridge, MA, USA.
[2] Department of Physics, Tokyo Institute of Technology, Japan.
[3] Los Alamos National Laboratories, Los Alamos, NM, USA.
[4] Centre d'Etude Spatiale des Rayonnements, Toulouse, France.
[5] Consiglio Nazionale delle Ricerche, istituto TESRE, Bologna, Italy.
[6] University of California, Berkeley Space Sciences Laboratory, Berkeley, CA, USA.
[7] University of California, Santa Cruz, CA, USA.
[8] NASA/Goddard Space Flight Center, Greenbelt, MD, USA.
[9] Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL, USA.
[10] Instituto Nacional de Pesquisas Espaciais, Sao Jose dos Campos, Brazil.
[11] Tata Institute of Fundamental Research, Mumbai, India.
[12] Faculty of Engineering, Miyazaki University, Japan.
[13] Department of Physics, Aoyama Gakuen University, Tokyo, Japan.
[14] Japan Science and Technology Corporation (JST), Japan.
[15] National Space Development Agency of Japan (NASDA), Japan.
[16] RIKEN (The Institute of Physical and Chemical Research), Wako, Saitama, Japan.

Thus, prompt optical, IR, and radio follow-up identifications can be anticipated for a large fraction of HETE GRBs.

Here we report the localization of the first HETE-discovered [1] GRB for which a counterpart has been found. Based on the combined data from HETE and the Interplanetary Network (IPN), a diamond-shaped error box roughly 15 arc minutes on an edge was established for GRB010921. Subsequent searches of this error box by ground-based optical and radio instruments revealed a fading counterpart whose properties are reported elsewhere (Price et al 2001a, 2002; Kulkarni et al 2002; Park et al 2001a, 2002; Djorgovski et al. 2001).

2. HETE MISSION AND INSTRUMENTS

The HETE spacecraft is a small satellite, measuring roughly a meter high by half a meter in diameter, with a mass of 125 kg. Constructed and launched at a cost less than $\frac{1}{3}$ that of a NASA Small Explorer (SMEX), HETE was primarily developed and fabricated in-house at MIT by a small scientific and engineering team, with major hardware and software contributions from international partners in France and Japan (Doty et al. 2002). Contributions to software development were also made by scientific partners in the US, at the Los Alamos National Laboratory, the University of Chicago, and UC-Berkeley. Operation of the HETE satellite and its science instruments, along with a dedicated tracking and data telemetry network, is carried out by the HETE Science Team itself (Crew et al. 2002). Routine activities are largely automated, with oversight and monitoring by members of the Science Team at MIT and at RIKEN.

The gamma-ray burst detection and localization system on HETE consists of three complementary instruments: the French Gamma-ray Telescope (FREGATE), Wide-Field X-Ray Monitor (WXM), and the Soft X-Ray Camera (SXC). The manner in which the three HETE science instruments operate cooperatively is described in Ricker et al. (2002). Since GRB010921 was outside the field-of-view of the SXC, that instrument will not be discussed in this paper.

French Gamma-ray Telescope (FREGATE). FREGATE consists of four, co-aligned cleaved NaI(Tl) scintillators. Its prime objectives are the detection and spectroscopy of GRBs and the monitoring of variable X-ray sources. FREGATE is optimally sensitive in the 6-400 keV energy band, and provides limited ($\approx \pi$ sr) localization information. The FREGATE instrument was developed by Centre d'Etude Spatiale des Rayonnements (CESR; Toulouse, France). Additional details regarding FREGATE are given in Table 4, and in Atteia et al (2002).

Wide-Field X-Ray Monitor (WXM). The Wide-Field X-ray monitor (WXM) consists of two, crossed one-dimensional coded aperture cameras. The cameras are designated WXM-X and WXM-Y, respectively, indicating the spacecraft axis along which each is optimized for GRB localization. Two position sensitive proportional counters (PSPC) are utilized in each camera. The prime objectives of the WXM are the detection and spectroscopy of GRBs and the monitoring of variable X-ray sources in the low energy band. The WXM is optimally sensitive in the 2-25 keV energy band, and typically provides $\leq 10'$ burst localizations. The WXM was developed by RIKEN(Japan) and the Los Alamos National Laboratory. Additional details regarding the WXM are given in Table 4, and in Kawai et al (2002) and Shirasaki et al. (2000).

3. OBSERVATIONS

Standard HETE operations consist of a survey for transient gamma-ray and X-ray events in the 2-3 steradians centered on the antisolar point. Observations take place in that half of the HETE orbit where the instruments' FOV is clear of the Earth. On September 21 at 18950.56 SOD (05:15:50.56) UT, the FREGATE instrument on HETE detected a bright ($> 80\sigma$) GRB. In this section we describe the localization and properties of GRB010921 as determined from HETE and IPN observations of this burst.

3.1. *Localization*

GRB010921 was recorded as trigger event H1761 by the FREGATE instrument on HETE, and was promptly reported as a GCN Notice at 05:16:08 UT, approximately 17 seconds after the burst. The burst was also detected at a SNR=7.1 in the WXM X detector. The projection of the burst direction was offset 24 degrees from the WXM X-Z plane, resulting in a good ($\pm 10'$) localization in the X direction and crude limits on Y, thereby localizing the source to a thin, long strip. The projection of the burst direction was offset 39 degrees from the WXM Y-Z plane, outside the fully-coded FOV. Thus, the WXM Y camera provided no useful information regarding the Y location of the burst. Analysis of the Y location required the rapid development and testing by the HETE Team of non-standard ground analysis software that would rely on the limited WXM X camera data, delaying the dissemination of the two-dimensional localization reported in GCN Circular 1096 until approximately 5.1 hours after the GRB. The initial estimate reported in GCN Circular 1096 was that the localization strip extended $\sim 10^{\rm o}$ in the long direction, and $20'$ in the short direction (Ricker et al 2001a).

Further refinement of the strip dimensions reduced the WXM error region to a $5.2^{\rm o}$ by $17'$ box, with the 4 corners at coordinates:

$$\alpha_{J2000} = 22^{\rm h}55^{\rm m}34.7^{\rm s},\ \delta_{J2000} = 40^{\rm o}25'55''$$
$$\alpha_{J2000} = 22^{\rm h}54^{\rm m}05.7^{\rm s},\ \delta_{J2000} = 40^{\rm o}26'42''$$
$$\alpha_{J2000} = 23^{\rm h}04^{\rm m}30.4^{\rm s},\ \delta_{J2000} = 45^{\rm o}23'35''$$
$$\alpha_{J2000} = 23^{\rm h}02^{\rm m}60.0^{\rm s},\ \delta_{J2000} = 45^{\rm o}24'18''$$

Both *Ulysses* and the gamma-ray burst monitor on *BeppoSAX* observed GRB010921, and an initial IPN error box was circulated 15.2 h after the burst (Hurley et al. 2001). Triangulation has now been performed using the final data, resulting in a *Ulysses* to HETE-FREGATE annulus centered at α_{J2000}, δ_{J2000} = $15^{\rm h}29^{\rm m}23.6^{\rm s}$, $67^{\rm o}36'14''$, with radius $60.082 \pm 0.118\ ^{\rm o}$ ($3\ \sigma$). This annulus intersects the $3\ \sigma$ WXM error box to give a 310 square arcminute error region whose coordinates are given in Table 1; the diamond-shaped error region is shown in figure 1. This error box is larger than reported in Hurley et al. (2001) due to the fact that the initial WXM error box was quoted for

[1] HETE detects $\sim$50 GRBs yr^{-1}, of which $\sim$15 yr^{-1} are localized by the WXM (Ricker et al. 2002)

90% confidence (ie 2σ). Both the Ricker et al. (2001a) 2σ error region and the 3σ error region given here are consistent with the position of the optical transient discovered by Price et al. (2001a), with the OT lying 3.6′ from the centerline of the WXM error strip, and 3.1′ from the centerline of the IPN error annulus.

3.2. *Time History, Peak Flux and Fluence*

The time history of GRB010921 observed by the HETE science instruments is shown in figure 2. The six panels in figure 2 illustrate the energy dependence of the burst profile and duration. For FREGATE, all 4 detectors were summed; for the WXM, only the signal from one illuminated anode (out of six total) in the X-camera was utilized, so as to maximize the signal-to-noise ratio, since GRB010921 was quite far (43 degrees) off-axis from the instrument boresight. Quantitative measures of the burst temporal properties (i.e., t_{50} and t_{90}; Paciesas et al. 1999) are given in Table 2. At the highest energies measured by FREGATE (32-400 keV band), the GRB010921 light curve exhibits a high degree of symmetry, with t_{50}=7.4s and t_{90}=21.8s. At lower energies, the t_{50} duration becomes somewhat larger, increasing by $\sim$ 30%; on the other hand, t_{90} is largely unchanged over the 4-400 keV band. Overall, the light curve for GRB010921 exhibits a hard-to-soft spectral evolution that is common in many GRBs.

The prompt emission by GRB010921 was measured over more than 2 decades in energy by HETE (Table 3). It is notable that GRB010921's peak energy flux of 2.0 10^{-7} erg cm^{-2} s^{-1}) in the 4-25 keV X-ray band was $\sim \frac{1}{3}$ the peak energy flux in the "traditional" 50-300 keV gamma-ray band. A comparison of the peak photon flux in the two bands is even more striking: $\sim$4 times as many 4-25 keV photons were emitted as were 50-300 keV photons. (For GRB010921, the smaller SNR in the WXM compared to the SNR in FREGATE arises from the fact that GRB010921 was offset 43° from the boresight of the WXM.)

4. DISCUSSION

The temporal characteristics of GRB010921 clearly mark it as belonging to the class of long duration GRBs (Hurley 1992, Kouveliotou et al. 1993). It is also quite "X-ray rich," in that it exhibits a value of $L_{x(4-25keV)}/L_{\gamma(50-300keV)}$ $\sim$0.3. However, it is by no means deficient in its 50-300 keV gamma-ray flux: in fact, its peak flux of 3.6 ph cm^{-2} s^{-1} in the 50-300 keV range would place it within the top decile of bursts in the 4Br Catalog (Paciesias et al 1999). Thus, GRB010921 does not qualify as an X-ray Flash (XRF; Heise et al. 2001). Based on its apparent redshift of z= 0.450 (Djorgovski et al. 2001), the implied isotropic emitted energy of GRB010921 in the 8-400 keV band is 7.8 10^{51} ergs (assuming Ω_M=0.3, Ω_Λ=0.7, H_o=65 km s^{-1} Mpc^{-1}; for beamed emission, the total energy should be multiplied by the as-yet-unknown beaming fraction.) The redshift of GRB010921, the second lowest among established GRBs, makes it a strong candidate for extended searches for a possible associated supernova. Furthermore, GRB010921 was, like all HETE-discovered GRBs, transiting near midnight at the initial epoch of the burst, resulting in its being well-situated for followup studies by ground-based telescopes for several months following the burst. Thus, additional insight into the nature of GRB010921 can be anticipated from long-term optical photometry by large telescopes.

5. CONCLUSIONS

The localization of GRB010921 by HETE and the IPN has led directly to a successful identification of a low-redshift afterglow counterpart. The prompt initial GCN alert for GRB010921 was distributed worldwide within 17 s of the burst; however, the determination of the HETE WXM localization was delayed by 5.1 hours due to the need to prototype new software to accommodate GRB010921's extreme off-axis position in one of the WXM cameras. A confirmation, and definitive refinement of the WXM localization, using IPN data available 15.2 hours after the GRB enabled ground-based observers to successfully target GRB010921 during the first night following the burst, and to establish a counterpart well within the HETE-IPN error region. Hopefully, over the coming months the identification of optical counterparts resulting from prompt ($\leq$100 s), accurate HETE localizations will become routine. With the currently-projected long orbital lifetime (>10 years) and excellent health of the HETE spacecraft and instruments, we look forward to providing a uniquely valuable service to the worldwide community of GRB observers.

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REFERENCES

Atteia, J-L, et al. 2002, *In-flight Performance and First Results from the FREGATE Instrument on HETE*, in WH2001**.

Barthelmy, S. D., et al. 2002, *GCN: A Status Report*, in WH2001**.

Bloom, J.S., et al. 2001, GCN Circ. 1135.

Costa, E., Frontera, F., Heise, J., et al. 1997, Nature, **387**, 783.

Crew, G.B., et al. 2002, *HETE Mission Operations*, in WH2001**.

Djorgovski, S.G., et al. 2001, GCN Circ. 1108.

Heise, J., in't Zand, J., Kippen, R., and Woods, P., *X-Ray Flashes and X-Ray Rich Gamma-Ray Bursts*, in Gamma-Ray Bursts in the Afterglow Era, (Rome, Italy, 17-20 October 2000), ESO Astrophysics Symposia, Springer (Berlin), p. 16, 2001.

** WH2001 = *Gamma-Ray Burst and Afterglow Astronomy 2001: A Workshop Celebrating the First Year of the HETE Mission*, Woods Hole, MA, November 2001, to be published in the AIP Conference Proceedings (AIP Press: New York).

Hurley, K. 1992, *Gamma-Ray Burst Observations: Past and Future*, in Gamma-Ray Bursts, Eds. W. Paciesas and G. Fishman, AIP Conf. Proc. 265 (AIP Press- New York), 3.
Hurley, K., et al. 2001, GCN Circ. 1097.
Kawai, N., et al. 2002, *In-orbit Performance of the WXM Instrument on HETE*, in WH2001**.
Kouveliotou, C., et al. 1993, Ap. J. Lett., **413**, L101.
Kulkarni, S., et al. 2002, in preparation.
Paciesas, W.S. et al. 1999, ApJS, **122**, 465P.
Park, H. S., et al. 2001a, GCN Circ. 1114.
Park, H. S., et al. 2002, submitted to Ap. J. Letters (astro-pf/0112397).
Price, P.A., et al. 2001a, GCN Circ. 1107.
Price, P.A., et al. 2002, submitted to Ap. J. Letters (astro-pf/0201399).
Ricker, G.R., et al. 2001a, GCN Circ. 1096.
Ricker, G.R., et al. 2002, *High Energy Transient Explorer (HETE): Mission and Science Overview*, in WH2001**.
Shirasaki, Y., et al. 2000, Proc. SPIE, **4012**, pp 166-177.
Vanderspek, R.K., et al. 2002, *What HETE sends to the GCN*, in WH2001**.
Villasenor, J.N., et al. 2002, *First Year of Operations of the HETE Burst Alert Network*, in WH2001**.
Woosley, S. E. et al. 1984, The High Energy Transient Explorer (HETE), in *High Energy Transients in Astrophysics* (Santa Cruz, CA 1983), ed. S. E. Woosley, A.I.P. Conf. Proc. 115 (AIP Press-New York), p. 709.

Table 1
GRB010921 Error box coordinates.

α_{J2000}	δ_{J2000}
$22^{h}\ 56^{m}\ 6.9^{s}$	$40^{o}\ 45'\ 21''$
$22^{h}\ 56^{m}\ 37.3^{s}$	$41^{o}\ 03'\ 28''$
$22^{h}\ 54^{m}\ 21.74^{s}$	$40^{o}\ 36'\ 25''$
$22^{h}\ 54^{m}\ 51.9^{s}$	$40^{o}\ 54'\ 32''$

Table 2
Temporal Properties of GRB010921.

Energy Band (keV)	t_{50} (s)	t_{90} (s)
4 - 10	8.8	18.8
10 - 25	8.2	15.7
32 - 400	7.4	21.8

Table 3
Energy Emission Properties of GRB010921.

Energy Band (keV)	Signal-to-Noise (in 3 measured bands)	Peak Photon Flux (ph cm^{-2} s^{-1})	Peak Energy Flux (erg cm^{-2} s^{-1})	Fluence (erg cm^{-2})
4 - 25	7.1	14.8	2.0 10^{-7}	2.0 10^{-6}
8 - 400	87.9	17.2	1.1 10^{-6}	15.4 10^{-6}
32 - 400	43.6	6.0	8.5 10^{-7}	11.4 10^{-6}
25 - 100	—	6.1	4.7 10^{-7}	6.2 10^{-6}
50 - 300	—	3.6	6.1 10^{-7}	8.4 10^{-6}

Table 4
HETE Instrument Characteristics

Characteristic	Fregate	WXM
Instrument type	Cleaved NaI(TI)	Coded Mask with PSPC
Energy Range	6 keV to > 400 keV	2 to 25 keV
Timing Resolution	10 μs	1 μs
Spectral Resolution	∼25% @ 20keV, ∼ 9% @ 662 keV	∼ 20% @ 8 keV
Effective Area (on axis)	160 cm^{2}	∼116 cm^{2}
Sensitivity (10 sigma)	∼ 1 10^{-7} erg cm^{-2} s^{-1} (50–300 keV)	∼ 8 10^{-9} erg cm^{-2} s^{-1} (2-10 keV)
Field of View	∼4 steradians	∼1.5 steradians

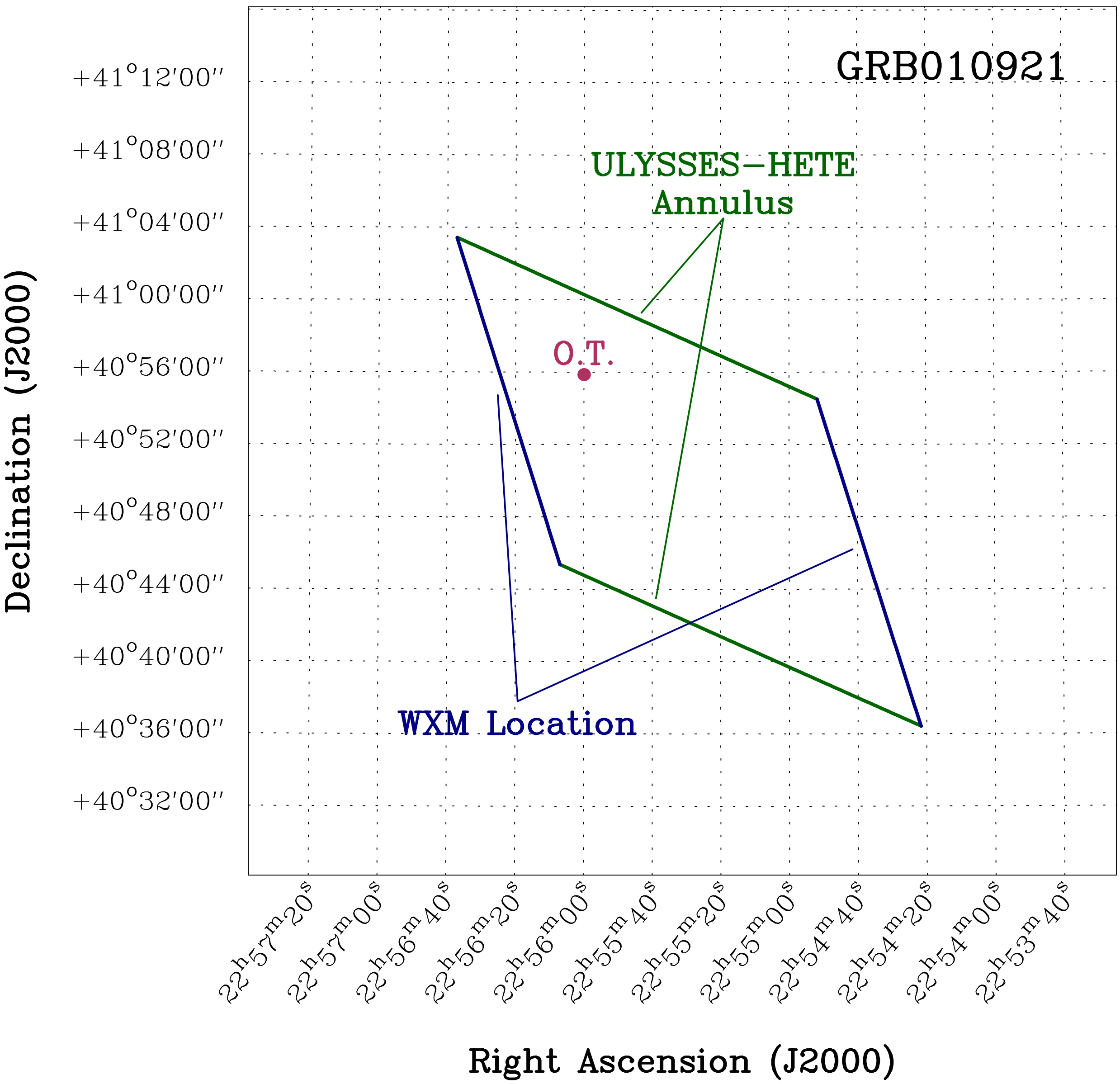

Fig. 1.— The final error box of GRB010921, determined from superposing the 3 σ WXM error box (north-south trending lines) and the 3 σ IPN annulus (east-west trending lines). OT indicates the position of the optical transient source found by Price et al. (2001a), at $\alpha_{J2000} = 22^{\rm h}\ 55^{\rm m}\ 59.9^{\rm s}$, $\delta_{J2000} = 40^{\rm o}\ 55'\ 53''$.

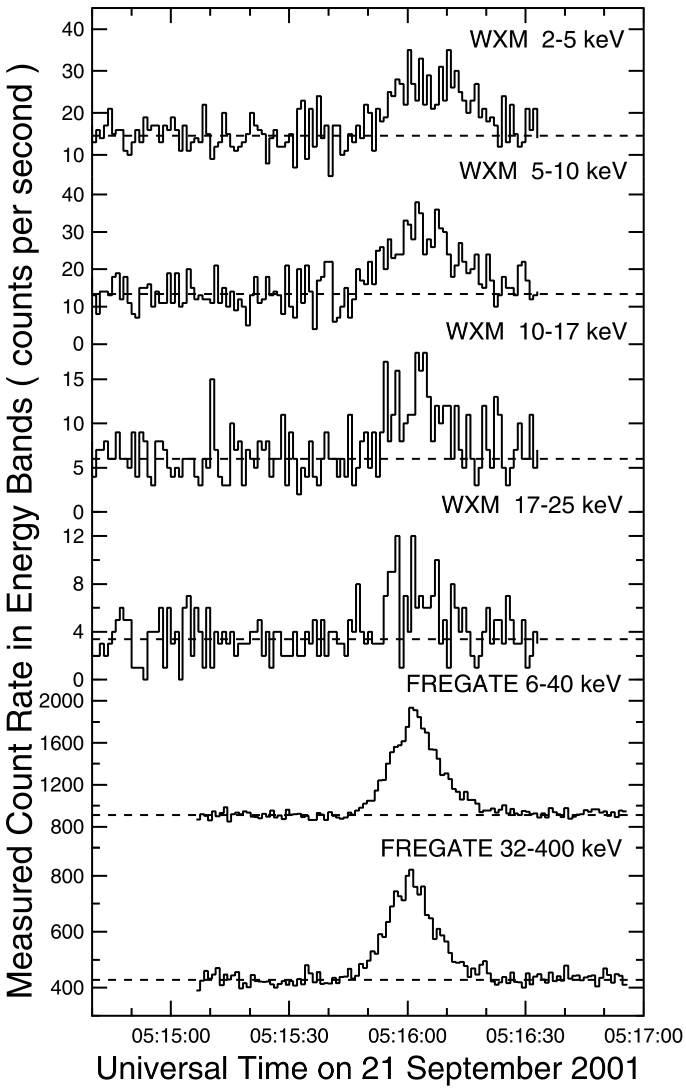

FIG. 2.— WXM and FREGATE light curves for GRB010921. The six panels correspond to six energy bands; the dashed lines indicate the backgound levels. For the WXM and FREGATE, the projected effective areas to GRB010921 were 10 cm^2 and 70 cm^2, respectively.